

December 31, 2008

Dr. Jon Morse  
Director, Astrophysics Division  
National Aeronautics and Space Administration

Dr. Dennis Kovar  
Associate Director of Science for High Energy Physics  
Department of Energy

Re: Joint Dark Energy Mission Figure of Merit Science Working Group

Dear Jon and Dennis,

On behalf of the Joint Dark Energy Mission Figure of Merit Science Working Group (the JDEM FoMSWG), I am pleased to transmit our report.

There are three components to the report:

1. This letter, which communicates our findings relevant for programmatic considerations and summarizes our findings contained in the second, technical part, of our review.
2. A lengthy technical paper, describing the scientific basis for our findings, and containing a quantitative description of the framework we have developed for assessing the merit of dark-energy missions.
3. A self-contained software package that will greatly facilitate efforts to compare and optimize different JDEM realizations (as well as ground-based dark-energy programs). This software will be communicated to the JDEM Program Office in electronic form.

With your concurrence, we plan to make this letter, the technical report, as well as the FoMSWG software, publicly available on the JDEM Program website. Additionally, we would like to post the technical paper on a public astronomy archive. We feel that making everything public would be of great benefit to the JDEM mission, and also would be of great use to the dark-energy community.

### *The Background*

The Dark Energy Task Force (DETF) proposed a Figure of Merit (FoM) in order to have a tool to make rough comparisons of different techniques and platforms and to compare dark-energy projects. It served well for its intended purpose, but as made clear during the Spring 2008 Symposium “A Decade of Dark Energy” held at the Space Telescope Science Institute, many members of the community feel that it would be prudent to revisit the issue of a FoM.

The FoMSWG was chartered to revisit the Figure of Merit (FoM) issue. From the FoMSWG Charter:

The purpose of this SWG is to continue the work of the Dark Energy Task Force in developing a quantitative measure of the power of any given experiment to advance our knowledge about the nature of dark energy. The measure may be in the form of a “Figure of Merit” (FoM) or an alternative formulation. The findings of the SWG will be reported to the agencies and will be considered for incorporation into NASA’s future JDEM Announcement of Opportunity (AO).

This three-part report contains our findings.

### *The Process*

The FoMSWG met in person twice (Washington in July and Chicago in August), and has had approximately 20 phone conferences. Members have put considerable thought, time, and effort into this effort (generating well over 600 mail messages). Group members were committed to producing findings useful for the JDEM Science Coordination Group and in preparation for JDEM Announcements of Opportunity.

Through electronic mailings by the American Astronomical Society and the American Physical Society Divisions of Astrophysics and Particles and Fields, we informed the community of the formation of the Working Group and invited input. This generated a fair amount of friendly advice and suggestions from interested parties.

### *Our Task*

The standard cosmological model assumes that dark energy is described by a cosmological constant. While this is the simplest possibility, the magnitude of  $\Lambda$  is difficult to understand, and, of course, we seek tests of this hypothesis.

Thus, when discussing ways to probe dark energy, we adopted the approach of the Dark Energy Task Force (DETF) and assumed that the observational program should be to:

1. Determine as well as possible whether the accelerating expansion is consistent with a cosmological constant, i.e., unevolving dark-energy density.
2. Measure as well as possible any time evolution of the dark-energy density.
3. Search for a possible failure of general relativity through comparison of the effect of dark energy on cosmic expansion with the effect of dark energy on the growth of cosmological structures.

The problem before us is to develop a quantitative measure of progress toward accomplishing this task.

### *Our Results*

In the report we establish a framework for assessing progress toward the above-mentioned goals.

The FoMSWG finds that the issues of the systematic errors in dark-energy measurements and the optimization of an integrated ground/space dark-energy *program* are critical, but we do not

address them here because those topics were outside our Charter. We stress that we worked only to establish a framework for assessing progress.

To establish the framework for assessing progress in understanding dark energy, we did the following:

1. *Chose a fiducial cosmological model.* We expect that this fiducial cosmological model will be used as a starting point for all JDEM considerations. In our findings we also emphasized the importance that all considerations use the same fiducial cosmological model as a starting point.
2. *Chose appropriate prior information to be used as a starting point in assessing JDEM possibilities.*
3. *Developed our best estimate as to the situation prior to JDEM.* We operated under the assumption that the nominal launch date for JDEM will be sometime in 2016. Dark energy remains a compelling astrophysical question (perhaps the *most* compelling) and the creativity and imagination of astronomers and physicists will continue to be directed toward investigations into the nature of dark energy. Predictions of what will be known about dark energy (or what will be known about systematic uncertainties associated with dark-energy measurements) eight years in the future are inherently unreliable. What we report about this subject is the informed judgment of the Science Working Group, but we must emphasize both the importance, and the inherent uncertainty, of such predictions.
4. *Described in great detail the rationale for our choices and provided Fisher matrices that should be used to quantify the value added of a JDEM.* Predictions about the reach of dark-energy experiments are only as reliable as the data models used to construct the Fisher matrices. Over time, as we learn more, the data models should adjust accordingly. Our descriptions are thorough enough to allow the data models to be updated while our basic framework remains useful.
5. *Provided a detailed description of graphs and numbers that will form the basis for a quantitative assessment of the science reach of JDEM.* In Section VI of the technical report we describe in detail how to interpret the graphs and numbers used to assess progress in dark energy.

### *Our Findings*

A FoMSWG finding (consistent with DETF) is that there should be two components in quantifying the scientific reach of a JDEM.

#### **I. Determine the effect of dark energy on the expansion history of the universe by determining the dark-energy equation-of-state parameter $w(a)$ , parametrized as described in the technical report.**

We find that this information is best conveyed by

1. Constructing Fisher matrices for each technique independently and in combination. The Fisher matrix is the basic tool that will be used to calculate the information needed to display the scientific reach of the proposed mission.

2. Displaying in a single figure the first few principal components of the dark energy equation-of-state parameters (described in the report) for each technique independently and in combination.
3. Displaying a graph of the ratio of the uncertainty after JDEM to the uncertainty before JDEM of the best determined principal components. Doing this for each probe of the dark energy independently and for the combination of techniques is most illuminating.
4. Assuming the DETF parametrization of the dark-energy equation of state, supplying the two numbers that describe the uncertainties in the DETF parameters  $w_0$  and  $w_a$  as well as the “pivot” redshift  $z_p$  and the uncertainty in the pivot value  $w_p$ .

**II. Determine if there is evidence that dark energy is the result of a modification of our understanding of gravity by measuring the history of the growth of cosmological structures.**

FoMSWG finds that this is best conveyed by computing the fully marginalized uncertainty in a single parameter, “ $\gamma$ ,” describing the growth of structure.

So in total, rather than a single figure of merit, the science reach of JDEM would be discerned from the figures and four numbers described above.

Our goal was to develop a powerful tool for evaluating and optimizing science investigations without imposing too great a computational or calculational burden.

Figures of merit computed by independent workers for the identical observational program often differ by 20% and sometimes by factors of 2. These discrepancies arise from different assumptions about nuisance parameters, different approximations for estimating statistical uncertainties, different views concerning the systematic errors floors of measurements, chosen values for fiducial astrophysical parameters, and assumptions about the effectiveness of novel data analysis techniques. When different analyses yield different results, the cause may not always be superior effectiveness in measuring dark energy, but technical details. We caution against over-interpretation of minor differences in FoMs, especially among different techniques or among codes that have not been cross-validated.

The strengths of a specific scientific investigation may be highlighted by computing different quantities from the ones we specify in this report. This may provide helpful supplemental information provided they are presented transparently in concept, motivation, and method.

### *Threshold*

In the Charter for the FoMSWG, we were requested to discuss the issue of threshold. From the FoMSWG Charter:

Determine a threshold value for this measure that any proposed JDEM investigation(s) must exceed to qualify for selection. If multiple measures are developed, provide the threshold values for each of these.

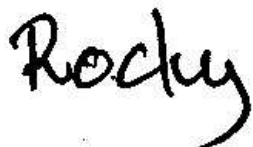
Because possible explanations of cosmic acceleration are diverse, no single number can fully describe the merit of a JDEM. Consistent with this, a FoMSWG finding is that no single number that can be used to quantify a threshold, as defined above. A threshold value requires knowledge of dark-energy parameters in 2016 and JDEM performance to greater precision than can be reliably calculated at this time.

However, we have identified four crucial considerations related to the threshold issue. These considerations are motivated by our finding that a successful JDEM mission must deliver a substantial increase in our knowledge about dark energy vs the pre-JDEM knowledge, according to the following measures and considerations:

1. We measure the merit of a JDEM by the amount it improves our knowledge of dark energy compared to pre-JDEM understanding. We specify how to compute statistics that illuminate any JDEM's ability to constrain  $w(z)$  and the growth of structure. Because possible explanations of cosmic acceleration are diverse, no single number fully describes the merit of a JDEM.
2. An optimized combination of techniques that results in a measure of both growth and cosmic distances is crucial for a successful JDEM. Maximizing overall mission performance should take priority over judging single techniques in isolation.
3. JDEM should make the most of the advantages that come from a space-based experiment. These include lower backgrounds, higher angular resolution, more stable observing conditions and instrumental calibrations, and the ability to execute an observing program in a timely way. The synergy between JDEM and contemporaneous ground-based experiments can be significant and should be considered in the design of JDEM.
4. The ultimate sensitivity of JDEM to dark energy will be determined by systematic as well as statistical errors. Including realistic assessment of the systematic errors in the evaluation of a JDEM, and explicitly demonstrating how those errors will be achieved, is therefore essential for any JDEM proposal. The systematic errors in any synergistic or competing ground-based observations need to be examined and studied with the same level of rigor as those affecting JDEM.

We would be happy to answer any questions.

On behalf of the FoMSWG,

A handwritten signature in black ink that reads "Rocky". The signature is stylized with a large, looped 'R' and a cursive 'y'.

Edward W. Kolb  
Arthur Holly Compton Distinguished Service Professor